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Art. VI.—*Quartz-Diorite Magma in Eastern Victoria.*

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Contents.

Introduction.

Localized developments of quartz-diorite are of frequent occurrence throughout Eastern Victoria (9, 12, 13, 14, 15, 17, 18), generally in association with more acid rocks; and despite their small total bulk, they reveal something of the processes of the progressive differentiation by which they, and presumably their granitic associates, were evolved.

A "Two-Pyroxene" Magma.

The magma which gave rise to the quartz-diorites was saturated with respect to silica, and was a "two-pyroxene" magma, i.e., as intratelluric cooling progressed, two immiscible series of pyroxenes crystallized out from it, namely diopsidic augites ($2V = 50°–60°$) and hypersthenes (in some instances enstatite, or even monoclinic enstatite-augite). At a later stage a single hornblende began to crystallize in place of the two immiscible pyroxenes, and by a discontinuous reaction the already crystallized pyroxenes were converted to hornblende.

This state of affairs is amply illustrated by the quartz-diorite of Granite Flat (on the Mitta Mitta River), in which large crystals of green-brown hornblende are found enclosing crystals of colourless augite ($2V = 60°$) and less numerous crystals of hypersthene. The contact of the hornblende and the enclosed pyroxenes is of a transitional nature. In the quartz-diorite-porphyrites of the Walhalla-Wood's Point dyke swarm (17), the brown hornblende phenocrysts enclose augite, and in one dyke an almost uniaxial pyroxene (i.e. monoclinic enstatite-augite).

The diorite dykes of North-east Benambra (9) show the same phenomena, the enclosed pyroxene being mostly augite ($2V = 50°$), but occasionally enstatite. Similarly, in the quartz-diorite of Reedy Creek, near Broadford, the hornblende phenocrysts enclose cores, partially altered, of augite and enstatite. Howitt (12) has described diorites from Swift's Creek, near Omeo, in which the hornblende encloses cores of augite, and examination of rock slides in the Howitt Collection at the University of Melbourne reveals this feature in a number of diorites from the Omeo region. In quartz-diorites from Swift's Creek, Riley's Creek, and Tongio Gap, the inclusions are of colourless augite and of enstatite; in those from Parsloe's and King's Spur, of augite and hypersthene; and at Jambarra River, in a more basic diorite, phenocrysts of augite and enstatite occur, with a lesser amount of later hornblende.

Other instances of this "two-pyroxene" magma in Victoria are provided by the hypersthene-dacites of the Dandenong Ranges, the Mt. Juliet-Donna Buang Ranges near Warburton, and probably that of the Macedon Ranges. In these, hypersthene is the dominant pyroxene, but occasional crystals of colourless augite ($2V = 50°–60°$) have been observed in the former two.

With continued intratelluric cooling of the magma the hornblende is replaced by a ferro-magnesian biotite, and this by muscovite; but where the cooling has been more rapid the hornblende has given place in some instances, as in the more basic hornblende-diorite dykes of North-east Benambra (9) to a groundmass phase of pigeonite ($2V = 40°$); while in others, as in the felspar-hornblende-porphyrites of Warburton (6), and the labradorite-porphyrites of Benambra (9), the hornblende itself occurs in the groundmass phase of the rock.

Petrological Theory.

These features of the quartz-diorite magma are fully in accordance with recent petrological theory. Thus, Sosman (27) and Asklund (1) have shown, by plotting the chemical analyses of igneous pyroxenes on a triangular basis (with MgO, FeO and CaO as poles), that there is apparently an immiscibility gap between the diopsidic pyroxenes (augites) and the enstatite-hypersthene series. This was confirmed by Tsuboi (28), who showed from a study of the "two-pyroxene" andesites of Japan, that two immiscible series of pyroxenes, diopsidic augites, and hypersthenes, crystallize during the intratelluric stage of cooling, their proportions depending upon the composition of the magma; but that during extrusion they give place, with certain exceptions, to a pigeonite which is a mixed crystal of the two. More recently, Bowen and Schairer (3), from their study of the ternary system MgO-FeO-SiO_2, have suggested an explanation of the phenomenon. They have demonstrated that the monoclinic Mg-Fe rich pyroxenes (pigeonites) are high temperature forms, while the augites and hypersthenes are relatively low temperature forms, stable at the temperatures existing in magmas. Under the conditions prevailing during intratelluric cooling these two low temperature pyroxenes crystallize side by side, but with rapid cooling, such as is caused by extrusion, a metastable phase of the high temperature form, pigeonite, crystallizes. In exceptional instances, where the cooling is not so sudden, the stable phases might persist into the groundmass, as Tsuboi indicated. Kuno (24) has shown that under equally exceptional conditions the high temperature pigeonites can persist as metastable phenocrysts.

Kennedy (20), on plotting the compositions of igneous hornblendes on a similar triangular basis to that used by Sosman and Asklund for the pyroxenes, found that they all fall within the immiscibility gap which separates the diopsidic augites from the hypersthenes; and are, apparently, equivalent to low-temperature mixed-crystals of these two pyroxenes. He suggests that when a rock in which hornblende is crystallizing is extruded these two pyroxenes should be formed in their equivalent proportions. In fact, however, the metastable pyroxene, pigeonite, appears (9), or the hornblende itself crystallizes in the groundmass phase. Presumably the hornblende is of approximately the same composition as the pigeonite.

Formation of Hornblende.

The stage of crystallization at which hornblende crystallizes is subject to variation. Thus, occasionally, as in the quartz-diorite of Granite Flat, it is not as far advanced as in the more basic diorites. What factors control this variation?

Since the mineralizers enter into the composition of the hornblende, their presence is essential—but not sufficient, as Kennedy and Read (21) have shown. The other controlling factors will be the composition of the magma, the temperature, the rate of cooling, and the pressure. A slow (intratelluric) rate of cooling is a favorable factor. Rapid cooling from a moderately high initial temperature may give rise to pigeonite; with a low initial temperature a groundmass phase of hornblende may form.

Grout states (10, p. 440) that brown hornblende, such as characterizes the common type of Victorian diorite, forms at above 850° C., while green hornblende, such as occurs in the more acid diorites, and in the granitic rocks, forms at below 800° C. Kozu, Yoshiki and Kani (22, 23) have shown, however, that common brown and green hornblendes, equally, are oxidized to basaltic hornblende at about 750° C., so that common hornblende probably forms at or below this lower temperature. Kennedy and Read (21, p. 127) cite an instance in which the hornblende became enriched in MgO and FeO as crystallization progressed; and the zoned hornblendes of some of the Benambra diorites (9) suggest a similar progressive change of composition. It seems probable, therefore, that CaO-rich types crystallize at higher temperatures than the iron-magnesia-rich varieties.

Whether pressure is important of itself, or merely because it is an essential accompaniment to retention of volatiles cannot be ascertained.

Hypersthene-Dacite.

Rosenbusch (26, p. 402) has directed attention to the fact that in andesites, phenocrysts of biotite or hornblende are generally accompanied by phenocrysts of acid plagioclase, while phenocrysts of hypersthene and augite are generally accompanied by basic plagioclase. The hypersthene-dacites of Central Eastern Victoria are a case in point.

The chilled border phases of these lavas give an approximate picture of the magma immediately prior to their extrusion. Its ferromagnesian content had almost completely crystallized out as hypersthene (and occasional augite) crystals, which were still in equilibrium with it. Practically all of the lime had also precipitated as basic plagioclase-zoned crystals, with cores of basic labradorite, and rims of andesine. The plagioclase, however, was not in equilibrium with the magma, and was in process of reacting with it to form more sodic plagioclase. Free silica had scarcely commenced to crystallize, so that the temperature was probably too high for hornblende to form.

The state of differentiation of the magma prior to the extrusion of the dacite may be pictured as a series of gradational layers, thus:—

Layer.	Crystalline Portion, i.e., Phenocrysts.		CaO per cent.	Al_2O_3 per cent.	SiO_2 per cent.
Hypersthene-Dacite	Hypersthene (augite)	Andesine	4	16	60–62
Augite Hypersthene-Diorite	Augite Hypersthene	Andesine (Basic)	8	16–20	52–55
?	?	?			

It is evident that in the upper layer all the lime and alumina has gone to form plagioclase, leaving the MgO and the FeO to form hypersthene. How could such a magma originate from a dioritic magma in which augite was the dominant pyroxene, with subordinate hypersthene?

The explanation probably lies in the fact that a large part of the lime in the hypersthene-dacite magma (probably as much as half the total) was locked up in "armoured" cores of labradorite in the plagioclase phenocrysts, leaving insufficient lime in the residual magma to produce both plagioclase felspars and lime-bearing pyroxenes. Such lime as was available was taken by the plagioclase, and the magnesia and iron left to form hypersthene as the increasingly dominant pyroxene. In other words, absence of equilibrium relations between the felspar and the magma led to marked fractional differentiation.

Three factors may have acted to produce this fractional crystallization of the felspars:—

(1) Relatively rapid intratelluric cooling, resulting from the approach of the magma close to the surface while it was still at a high temperature. This would prevent the basic plagioclase felspar from establishing equilibrium with the magma, and lead to zoning of the felspars.

(2) The reduction of pressure within the magma chamber, incident upon such thinning of the roof, might lower the crystallization temperature of the plagioclase felspars to some degree (11), and thus enable basic plagioclase to crystallize for a longer period than would be normal without such a reduction of pressure. This also would extract lime from the magma.

(3) Assimilation of argillaceous sediments might have this effect. Both Bowen (2) and Read(25) consider that the addition of alumina-rich material to basaltic magma "would result in the increase of the amount of magnesia in the pyroxene, and of anorthite in the plagioclase." Moreover, the potash content of such assimilated rocks would, as Daly (4, p. 450) has suggested, provide the essential potash of the andesitic rocks, potash not easily derived by differentiation of a basaltic magma.

That the roof of the magma chamber was thin at the time immediately preceding extrusion must apply equally to all dacites and andesites. The important factor for rapid cooling, therefore, is that the magma should be at a relatively high temperature during its approach to the surface, or that it should rise rapidly through the crust. Since quartz had barely commenced to crystallize from the hypersthene-dacites, the temperature of the magma was probably not greatly below 870° C.; and since the hypersthene was still stable, the temperature was probably well above 700° C. (5, p. 74).

Hornblende-andesites, in comparable situation within the crust, must have considerably lower temperatures than hypersthene-dacites, if common hornblende does not form above 750° C.; and the rate of cooling in these rocks must have been correspondingly slower, over a longer period, permitting a better establishment of equilibrium relations between early formed plagioclase and the magma. At the lower temperatures, moreover, a considerably more sodic plagioclase (about 10-20 per cent. richer in soda) should be able to crystallize from the hornblende-andesite than would be possible for the hypersthene-dacites.

Assimilation of argillaceous sediments by the magma must have occurred to some extent, but the degree cannot be gauged. The difficulty in determining what fraction of the assimilated material is incorporated in the hypersthene-dacites is illustrated by the following analyses of a xenolith of argillaceous sandstone, and of the typical hypersthene-dacite in which it occurs:—

—	1.	2.	3.	4.
SiO_2	61·38	62·73	64·00	63·74
Al_2O_3	20·28	17·41	19·81	19·91
Fe_2O_3	6·91	0·45	3·50	4·07
FeO	0·78	5·17	..	0·45
MgO	0·99	2·94	2·14	2·10
CaO	tr.	4·25	0·24	Nil
Na_2O	1·07	2·03	1·10	0·55
K_2O	3·46	3·30	4·41	3·89
H_2O	3·38	0·66	2·23	4·49
H_2O	0·57	0·16	0·85	0·47
CO_2	Nil	Nil	..	..
TiO_2	1·12	0·93	..	0·79
P_2O_5	tr.	0·23	0·01	tr.
MnO_2	tr.	tr.	..	..
FeS_2	Nil	0·30	..	Nil
Carbon	..	..	3·32	..
				0·11 Cl
	99·94	100·56	100·94	100·54

1. Indurated argillaceous sandstone, sedimentary inclusion in dacite, Mount Dandenong. Analyst—F. F. Field.
2. Hypersthene-dacite, road cutting, allotment 925A, Parish of Mooroolbark, 15 chains N.E. of Kalorama, Mount Dandenong. Analyst—F. F. Field.
3. Mica-schist, Omeo District. Analyst—A. W. Howitt.
4. Slate, Baker Mine, Wedderburn.

One might be tempted to ask—how much of the xenolith is derived from the dacite? The analyses of the mica schist from Omeo and the slate from Wedderburn are quoted to show that the composition of the xenolith is quite normal.

The other possibility arises—is the dacite a fused argillaceous sediment? If so, from where does it derive its lime and soda, and possibly, phosphorus?

The probability is that the silica of the assimilated sediments floated or rose to form the more acid, rhyolitic upper layer in the magma chamber, while the alumina crystallized as plagioclase, which would either sink or retain its level. Similarly the increased magnesian pyroxene would either sink or retain its position. In this way the lime of the magma would be increasingly diminished in the upper layers.

Origin of the Quartz Diorite Magma.

The origin of the quartz diorite magma in Eastern Victoria is not obvious; and bound up with it is the origin of the granites, granodiorites, rhyolites, toscanites, rhyo-dacites, and porphyries, which are apparently consanguineous with it. There are, however, certain outstanding features which any hypothesis must explain:—

1. The rocks in question are all saturated varieties, e.g., the diorites are always quartz-diorites. Quartz-free diorites have not been met with.

2. The basic rocks associated with the dioritic magma show a diversity of types. They include basalts, hornblende-mica-lamprophyres, gabbro-porphyrite, in one instance grading into porphyritic pyroxene-basalt, and in another into hornblende-peridotite, hornblende-hypersthene-gabbro, hornblende-peridotites, hornblende-pyroxenites, and hornblendites (18).

3. From the nature of their occurrences these ultra-basic types are not crystal accumulations, but represent magmas.

4. As emphasized in a previous paper (7), the dioritic magma in Victoria is intimately associated with an immediately previous orogeny. Tertiary magma intruding the same sediments, and probably additional granite, gave rise to a typical olivine-basalt-trachyte association. Therefore, either the original magma of the diorite suite was of different composition from that of the Tertiary period, or the differentiation was in some way effected by the orogenic period preceding it.

5. Whereas basic types are predominant, and monotonously uniform among the Tertiary rocks, they are distinctly a minor but diverse feature among the rocks associates of the diorite magma.

6. The gradational relationship which can be observed between the dioritic rocks and their more acid associates suggest that they were derived from a single magma stock by crystal differentiation.

7. A vast amount of assimilation, abyssal or otherwise, must have taken place to make room for the granitic intrusions; or else a volume of sediments equal to the total bulk of the intrusions must have been fused.

Daly (4, p. 450) directs attention to the association of andesites with (i) plateau basalts, and (ii) continental regions; and from this he infers that dioritic magma is probably derived from a primary basaltic magma, the process being aided by assimilation of Sialic xenoliths. Kennedy (19), for similar reasons, is led to believe that there are two distinct types of primary basaltic magma, which he designates as olivine-basalt magma type, and tholeiitic magma type. The olivine-basalt magma type differentiates towards trachytic magma, the tholeiite to andesitic or dioritic magma, the control being exerted by the different types of pyroxene which separate out from each magma type.

The five available analyses of the basalts associated with the Victorian diorite magma are not typically tholeiitic in character, being either too rich in MgO or else in Al_2O_3. A more fundamental objection lies in the presence of peridotite magma, which could not easily be derived from a tholeiite type of basalt. As Holmes writes (16, p. 555), "peridotite magmas cannot be accounted for otherwise than by refusion."

THE REFUSION THEORY.

The Refusion Theory, as outlined by Holmes (16), supplies an explanation of the association of the diorite magma with orogenic periods. Basing his ideas on the layered character of the crust in continental regions, as suggested by seismic evidence, he pictures the possible development, more or less in association, of three main types of parental magma: ultra-basic, basic, and acid. When, from some cause such as leads to an orogenesis, heat accumulates within the crust, fusion occurs in the peridotite layer. The fused magma commences to rise upwards, producing a "wave of magma," whose composition will depend upon which layer is undergoing fusion. Each layer, when fused, will give rise to a parent magma—a peridotite magma, a basaltic magma, and possibly an intermediate magma, or a granitic magma. All three may intermingle as the wave rises, or assimilate, giving rise to intermediate types, or, provided they can obtain access to the crust, may appear side by side as intrusions.

Three such magmas existed, side by side, during the Upper Palaeozoic period, in Victoria—whether of this or other origin.

Acidification of Basic Magma.

Two points are clear. Despite the association of the diorite magma with basalt, basalts do not, when they differentiate normally, give rise to vast amounts of acid magma. On the contrary, as the olivine-basalt-trachyte province indicates, they give rise to only minor amounts of acid magma.

Secondly, a vast bulk of sediments has disappeared to make room for the granitic intrusions accompanying the dioritic magma. These sediments may have been (i) fused *in situ*, and recrystallized, or (ii) assimilated. In either case they must have formed part of the magma which gave rise to the granitic intrusions. That they simply fused *in situ* and recrystallized to form granite is improbable, in view of the analyses quoted, which are comparable in composition with the average of all the available Victorian analyses of Silurian and Ordovician sediments. The magma resulting from such a fusion would have a composition corresponding with no known igneous rock. It is clear therefore that the second alternative is the more probable, i.e., that material was combined with the sediments to form granitic magma.

Addition of material could only be achieved by the sediments being assimilated, or being fused and mixed with other magma. This other magma, moreover, would require to contain abundant lime, little potash, and low alumina. A "plagioclase magma" of the type defined by Reynolds (27) in connexion with hybridization in the Newry Igneous Complex, would contain the desired proportions of lime, soda, and potash, but would be much too rich in alumina (22 per cent.). Plateau basalt (Kennedy's tholeiite magma type) more nearly fulfils the specifications. It contains 10 per cent. of CaO, about 1 per cent. of K_2O, and only 13-14 per cent. of Al_2O_3. Moreover, it is the type of basalt commonly found associated with dioritic magma throughout the world.

Imagine then such an admixture taking place, accompanied by crystallization differentiation. The addition of alumina to the tholeiite magma would cause lime to form basic plagioclase, thereby removing much alumina from the residual magma, and creating an intermediate magma richer in alumina than either the parent basalt or the residual magma.

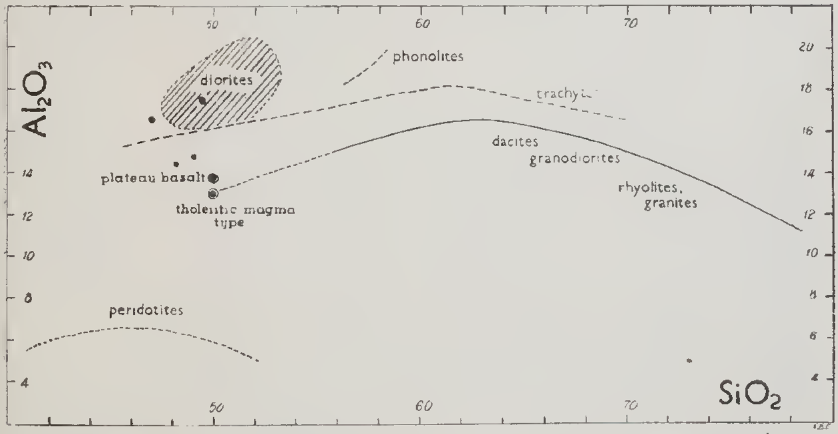

FIG. 1.—Quartz Diorite Magma in Eastern Victoria.—Variation of Al_2O_3 with SiO_2 for (1) Tertiary basalt-trachyte suite, shown by broken line; (2) Palaeozoic andesite-rhyolite suite, which is genetically related to the quartz-diorites, shown by full line. (3) Peridotites contemporaneous with the quartz-diorites, shown by the dotted line. (4) The quartz-diorites, by the shaded area. (5) Palaeozoic basalt associated with the quartz-diorite, andesite-rhyolite, and peridotite suites, by black dots.

In Fig. 1 the variation of Al_2O_3 with SiO_2 has been plotted for (i) the Tertiary olivine-basalt-trachyte suite in Victoria, represented by the broken line, (ii) for the Palaeozoic andesite-rhyolite suite (quartz-diorite magma), represented by the full line, and (iii) the peridotite-magma, by the dotted line.

It has been assumed that the tholeiite magma type is the parent magma for the andesite-rhyolite suite, and the full line has been extrapolated as a broken line to suggest the variation in Al_2O_3 with SiO_2 percentage which would have to occur if the more acid types were derived from simple crystallization differentiation

The oval shaded area embraces the Al_2O_3 contents of all the analysed Victorian quartz-diorites. It is clear that if the plateau-basalt is the parent of the andesite-rhyolite series, then the quartz-diorites are all exceptionally rich in Al_2O_3. Even if olivine-basalt magma were the parent magma, they still remain unusually rich in Al_2O_3.

The black dots represent the Al_2O_3 contents of the four reliable analyses of associated basalts. One falls within the diorite area and one close to its edge; the other two lie half-way between the tholeiite magma and the olivine-basalt-magma. All have been enriched in Al_2O_3 with regard to tholeiite magma type.

The removal of the lime as basic plagioclase would cause the magnesia and iron to crystallize as hypersthene in the presence of excess SiO_2. Some of the potash introduced might conceivably form biotite if the temperature permitted.

The greater part of the assimilated material would be rejected by the basaltic magma in the normal way, by crystallization differentiation, but would carry with it some additional lime and soda from the basalt. Until the alumina content was sufficiently reduced, lime plagioclase and hypersthene would continue to form, thus giving rise to hypersthene-dacites, which would grade into rhyolites. The characteristic pyrogenetic garnets in the more acid dacites (8) is adequate evidence that those rocks were saturated with respect to alumina. All the rock types produced subsequent to the assimilation would necessarily be saturated with respect to silica, so that quartz-basalts, quartz-diorites, quartz-andesites, and rhyolites would be expected.

The fact that the Tertiary olivine-basalt magma was scarcely affected by assimilation (7) makes it clear that the effect of the orogenic period must be to pre-heat, or even fuse the sediments at the roots of the newly-formed mountainous tract, or in some other way dispose them to ready assimilation or intermingling with the wave of basaltic magma rising from the deeper layers.

It is suggested that the diorite magma of Victoria, and its basic and ultrabasic associates, furnish evidence of refusion and intermingling of magmas, in the manner suggested by Holmes.

Summary and Conclusions.

Quartz diorites, though of limited development, are of such frequent occurrence throughout Eastern Victoria in genetic association with granitic intrusives and lavas, that any hypothesis as to the origin of the one must include the other.

Any such hypothesis must also account for the disappearance of a vast bulk of alumina-rich sediments which the granitic intrusives have replaced. Their disappearance cannot be accounted for by simple fusion and recrystallization, since they contain too little lime or soda and too much Al_2O_3 to give rise to granites; nor can it be explained by the soaking up into such sediments of a "plagioclase magma", since this would have raised the alumina content still higher.

The intrusion of the diorite-granite suite followed a major orogenesis, and was associated with the intrusion of minor quantities of basalt and peridotite. This is in marked contrast with the Tertiary intrusions of the same areas, which took place during a period free from orogeny, when the extrusions were dominantly basaltic, with only minor amounts of acid types (trachytes).

Since basaltic magma was undoubtedly associated with the intrusion of the diorites and granites, it is suggested that the development of heat accompanying the orogenesis (1) pre-heated the roots of the folded sediments in such a way as to predispose them to assimilation, and (2) caused the fusion of the periodotite layer of the crust, leading to the slow ascent of a wave of magma through the crust. The basaltic layer of the crust fused to form plateau basalt magma (Kennedy's tholeiite magma type), and this rose into and assimilated, either *in situ* or in depth, the preheated and possibly fused, granitic and alumina-rich sedimentary layers above it.

Crystallization differentiation, in combination with this process, would then have been adequate to produce the rock types now exposed. The addition of abundant alumina to the rising magma would cause the precipitation of lime plagioclase. The resultant withdrawal of lime from the sphere of the ferro-magnesians would lead to the formation of a two-pyroxene magma: such of the pyroxene as could obtain lime would form diopsidic augite: such as could not would form hypersthene or enstatite, the two series being immiscible under intratelluric conditions. With continued removal of the lime, subsequent to continued addition of alumina, the hypersthene would become the dominant ferro-magnesian. Throughout this period the silica and potash added to the magma by assimilation, and the soda already in it, would become increasingly concentrated in the residual magma. As the temperature decreased the soda would enter increasingly into the constitution of the plagioclase. Finally the silica would commence to crystallize as phenocrysts. At this stage, also, if the excess of Al_2O_3 continued, almandine garnets might form, since the continued removal of magnesia as hypersthene would have relatively increased the Fe/Mg ratio of the residue. Potash would also begin to crystallize out in combination with the excess Al_2O_3 and Fe as biotite, and with Al_2O_3 and SiO_2 as orthoclase.

Extrusion of the magma at these various stages would readily give the rhyolite, biotite-rhyodacite, hypersthene-dacite, and the quartz-porphyry, quartz-biotite-porphyrite, quartz-diorite associations so characteristic of Victoria, while abyssal consolidation would give rise to the widespread granitic rocks.

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